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An Overview of Hall Thruster Development at NASA's John H. Glenn Research Center

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Abstract

An overview of Hall thruster research and development tasks conducted by the National Aeronautics and Space Administration's John H. Glenn Research Center during fiscal year 2005 is presented. The tasks described include the investigation of scaling Hall thrusters to power levels up to 100 kW, the development of a hollow cathode capable of providing emission current up to 250 A, an experimental performance investigation and erosion characterization of a high-power, high-specific impulse Hall thruster, and the design and demonstration of a 0.3 to 3.0 kW Hall thruster. For each task, a description of the program background, mission application, technical accomplishments, and out year plans are provided.

I. Introduction

In January of 2004, the Vision for Space Exploration was revealed and the National Aeronautics and Space Administration (NASA) began to implement a program to explore the solar system and beyond (ref. 1). A measured approach, by which NASA will execute robotic and human Lunar, Mars and other exploration missions, was outlined. To achieve these goals in an affordable and sustainable fashion, new capabilities and exploration architectures will be developed. One of these new capabilities, which supports the exploration goals is a solar electric propulsion (SEP) transfer vehicle for high efficiency cargo delivery (refs. 2 and 3). The propulsion requirements for an SEP transfer vehicle as well as those for some of the more ambitious robotic missions being planned, exceed the capabilities of existing propulsion systems. NASA John H. Glenn Research Center's (GRC) Electric Propulsion Branch is developing electric propulsion technologies, which enable the future missions being pursued by the Agency (refs. 4 to 6). Hall thruster propulsion systems that have been identified as enhancing or enabling technology for these mission are currently being developed.

During fiscal year 2005 (FY05), NASA GRC conducted several Hall thruster research and development tasks, which are aligned with NASA's missions. These tasks were conducted under the sponsorship of the Exploration Systems Mission Directorate's Project Prometheus and the Exploration Systems Research and Technology Program (ESR&T) and Science Mission Directorate's In-Space Transportation Propulsion Program (ISTP). The characteristics of the Hall thruster technology being developed are summarized in table 1. In support of Project Prometheus, the technical challenges associated with increasing the specific impulse of high-power Hall thrusters are being addressed. A breadboard discharge power supply is also being developed to advance high-power Hall thrusters to an intermediate technology readiness level (TRL) (ref. 7). The ESR&T Program is responsible for the development of system concepts, architectures and break-through technologies necessary for human and robotic exploration of the solar system and beyond. Under the sponsorship of the ESR&T Program, NASA GRC is developing 100 kW class Hall thruster and hollow cathode technology and the means to substantially increase thruster lifetime. The In-Space Transportation Program (ISTP), managed by the NASA Marshall Space Flight Center, develops advanced propulsion technologies to replace conventional propulsion systems for space science missions within and beyond Earth orbit. In FY05, a 0.3 to 2.8 kW Hall thruster was fabricated and experimental investigations were conducted under the ISTP funded, High Voltage Hall Accelerator (HiVHAC) project. A description of NASA GRC's program year 2005 accomplishments in the area of Hall thruster propulsion is presented.

TABLE 1.—HALL TECHNOLOGY BEING DEVELOPED
BY EACH NASA SPONSOR.

	In-Space Propulsion Program	Project Prometheus	Exploration Systems Research & Technology
Power Level (kW)	0.3–2.8	20–50	100–150
Specific Impulse (sec)	1500–2800	2500–4000	2500–3000
Current TRL	4	3	2

II. Exploration Systems Research and Technology Program: Multi-100 kW Long Life Hall Thruster Technology Project

A. Programmatic Background

The ESR&T Program was established within the ESMD to perform the technology development necessary to realize NASA's exploration goals. ESR&T is comprised of three programs including the Advanced Space Technology Program (ASTP), the Technology Maturation Program (TMP) and the Innovative Partnership Program. The ASTP is focused on research, development and experimental or analytical validation of innovative concepts. The goal of the ASTP is to transition technologies to the TMP for further development and space flight demonstration. The Innovative Partnerships Program manages technology transfer between NASA and U.S. industry and includes the Small Business Innovative Research programs.

ESR&T development projects were awarded via a competitive selection process, executed through NASA Broad Area Announcement solicitations. Non-NASA institutions were eligible to submit proposals in response to the Extramural Call for Proposals (ECP) and NASA Centers were invited to lead proposals offered in response to the Intramural Call for Proposals (ICP). NASA GRC submitted a proposal entitled "Multi-100 kW Long Life Hall Thruster Technology" in response to the ICP, which was awarded in January 2005. The project was offered in response to the Power, Propulsion and Chemical Systems element of the ASTP, which solicited for electrical space propulsion systems for exploration missions (ref. 8). The objectives of this project are to increase the single unit Hall thruster power level from 50 kW to greater than 100 kW and to increase operational Hall thruster lifetime from less than 1 year to greater than 5 years. The total project duration is 4 years, consisting of a 1 year Phase I and an optional 3 year Phase II. The project is being performed in collaboration with Johnson Space Flight Center and the Jet Propulsion Laboratory.

Under the ECP process, Aerojet, in collaboration with Lockheed Martin Missiles and Space, NASA GRC and Colorado Power Electronics, was selected to develop a 600 kW Hall thruster system (ref. 9). NASA GRC's role in this activity is to provide the thruster design for the Hall thruster system and perform subscale development testing.

B. FY05 Technical Accomplishments

Tasks that have been performed during Phase I include a survey of previous mission analyses, high-power Hall thruster scaling and design, and hollow cathode development tasks. The mission analysis task consisted of a review of previous solar electric propulsion (SEP) transfer stage studies. This work was performed to formulate a set of derived requirements including the power level, specific impulse, lifetime, mass, and thruster footprint area to guide the high-power Hall thruster development. SEP transfer stage applications including cargo delivery for robotic Lunar missions (ref. 10) and human Mars missions (ref. 11) were considered. An SEP vehicle concept, designed as part of a Lunar L1 gateway mission architecture study, was examined. For this study, a conceptual 584 kW vehicle utilized 2700 second Hall thrusters to deliver 30 MT of payload from LEO to Lunar L1 (ref. 10). As an option for a human Mars mission, an architecture which combined SEP, a cryogenic upper stage, and aerobrake technology was evaluated. Using this strategy, a 0.5 to 1.0 MW SEP system utilized 2000 to 2500 second electric thrusters to perform the transfer of Mars transportation elements from low earth orbit to a high energy elliptical earth parking orbit (ref. 11). Based on the review of these studies, a 100 kW class, 2000 to 3000 second Hall thruster was selected for further consideration.

For Hall thrusters of this power level, the thruster footprint area and mass were chosen as figures of merit to assess the initial designs. Analyses were performed to investigate the dependency of the overall thruster footprint area on the discharge channel configuration. The discharge channel geometries considered included: 1) a traditional annular channel, 2) high-aspect ratio (two semicircular sections connected by two straight sections) and 3) nested configurations (multiple circular discharge channels within a single thruster unit). For a given channel area, the relationship between the total enclosed thruster area was calculated as a function of channel width for each configuration. For the cases considered the nested configuration, which utilizes two independent discharge channels within a single thruster, corresponded to the smallest total enclosed area. Assuming the channel width of a demonstrated high-power Hall thruster, the footprint area of a nested channel thruster was approximately half that of a traditional channel design. To evaluate the merits of each configuration on the basis of mass, a magnetic circuit was designed for the traditional annular and nested configurations. These configurations are depicted in figure 1. To facilitate direct comparison of magnetic circuit mass, both designs used the same channel width, depth and magnetic field characteristics. The magnetic circuit mass of the nested configuration was approximately 25 percent less than the mass of an equivalent circuit in a traditional annular configuration. Although a Hall thruster with multiple channels is a lower TRL concept, the nested channel approach was selected as a baseline for further development due to the reduction in footprint area and mass relative to a traditional annular configuration.

A preliminary mechanical design was completed for both the nested and traditional annular channel thruster configurations. Three-dimensional solid models, intended to be used as the basis for the thermal and structural analysis, were generated. The design was assessed from a manufacturability and material availability standpoint and revised accordingly. The outside diameter of the discharge channel exceeded the manufacturing capability of commercial boron nitride vendors. The mechanical design of a segmented boron nitride discharge channel was developed to address this technical issue. A preliminary anode design was developed and the neutral propellant distribution of the nested and traditional annular configurations was assessed using a Monte Carlo method. The preliminary results of these analyses indicated that uniform propellant distribution can be achieved for the thruster channel configurations and anode designs that are being considered.

A laboratory model hollow cathode assembly was designed with emission current and lifetime parameters, which are consistent with the ESR&T Hall thruster. The emitter geometry was selected based on a simple prediction for thermionic emitters performed using the Richardson equation (ref. 12). The emitter size was designed to provide emission current up to 250 A while maintaining a current density on the emitter surface consistent with flight qualified hollow cathode assemblies that demonstrated operation for more than 28,000 hours (ref. 13). In addition, the designed emitter will operate at surface temperatures consistent with hollow cathodes that have demonstrated lifetimes of more than 30,000 hours (ref. 14). An existing two-dimensional thermo-chemistry/diffusion model was also used to predict barium/barium-oxide evolution and loss rate from the emitter impregnate. The model results of this analysis confirmed that the selected emitter size can accommodate the current and lifetime requirements of the ESR&T Hall thruster (ref. 15). A modular, mechanical design, which incorporated an enclosed keeper configuration, was developed. Features of the design, depicted in figure 2, include reduced parts count and a simplified assembly processes that facilitates component interchangeability.

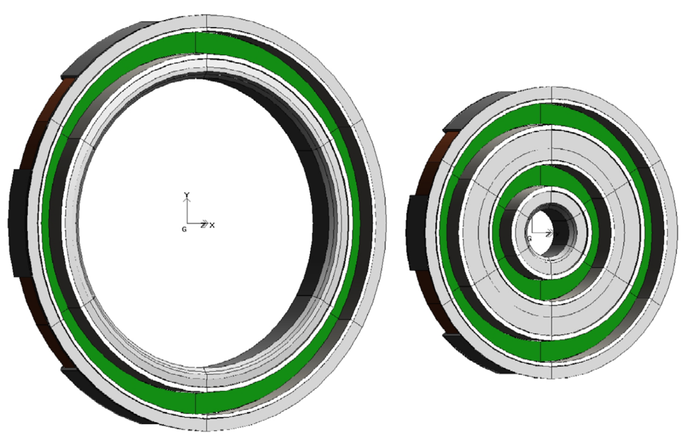

Figure 1.—Annular and nested Hall thruster configurations.

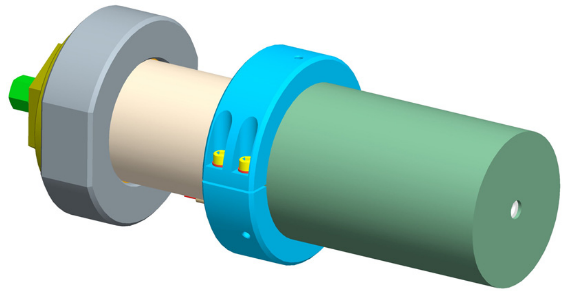

Figure 2.—Solid model rendering of the 200 Ampere ESR&T hollow cathode.

C. Out-Year Plan

Phase I of the Multi-100 kW Long Life Hall Thruster Technology project ends in January 2006. The technical progress and relevance to NASA's exploration goals will be evaluated at a project continuation review scheduled for November 2005, and a recommendation will be made regarding continuation to Phase II.

The total duration of the Phase II effort is 3 years. In year 1 of Phase II, thermal and mechanical analyses will be performed and the mechanical design of the 100 kW class thruster will be refined. The fabrication of the laboratory model hardware will be performed and facility preparations will be made for the experimental test program, which will occur in the latter portions of Phase II. A subscale thruster, which utilizes an actuated ceramic discharge channel to increase the operational lifetime, will also be fabricated and performance and lifetime experimentally demonstrated.

III. In-Space Transportation Program High Voltage Hall Accelerator (HIVHAC) Development Project

A. Programmatic Background

The HIVHAC Development Project was competitively selected under NASA's In-Space Propulsion Technologies Cycle 2 NASA Research Announcement (NRA) solicitation. The Cycle 2 NRA solicited for "kW Solar Electric Propulsion System technology" which offered mission benefit compared to NASA's Evolutionary Xenon Thruster (NEXT), gridded ion thruster propulsion system for an interplanetary robotic exploration deep space design reference mission (DSDRM). GRC performed mission analyses that compared Hall thruster technology to the 4000 second NEXT ion thruster system for Neptune and Saturn DSDRM's. These analyses indicated that a Hall propulsion system, used for both Earth escape and interplanetary transfer, offers a trip time reduction or increase in payload for these space science DSDRM's relative to NEXT. Based on this analysis, GRC proposed to develop a 6 to 8 kW Hall thruster that operated at specific impulses ranging from 2200 to 2800 seconds. In May 2003 the HIVHAC development project was selected for award.

In March 2004, a conceptual design review of the HIVHAC Hall thruster development was conducted. At the same time, the In-Space Propulsion (ISP) Project Office initiated the In-Space Refocus activity, to evaluate the applicability of on-going, ISP sponsored electric propulsion technology development activities to NASA space science missions. Based on the results of this study, projects were redirected to maximize the relevance to NASA missions. Because the 6 to 8 kW HIVHAC Hall thruster was offered as an option to NEXT, which is applicable to large flag-ship DSDRM type missions (ref. 16), the HIVHAC technology was less well suited for other NASA Science Mission Directorate applications. As a result, the HiVHAC project was redirected following the conceptual design review to a lower thruster power level and mission analysis was performed to evaluate the suitability of the technology for Discovery class missions (ref. 17), and New Frontiers class missions (ref. 18).

B. FY05 Technical Accomplishments

Based on the results of the In-Space refocus activity, Hall thruster propulsion system characteristics that are beneficial for NASA science missions were identified. These characteristics include the ability to operate at power levels lower than NSTAR (0.5 kW) and NEXT (0.6 kW), efficient thruster operation over a wide range of discharge currents and voltages (efficient throttling) and low cost. The design, fabrication and experimental demonstration of a Hall thruster with these attributes were pursued. The selection of the thruster power level was guided by the In-Space refocus mission analysis (refs. 17 and 18) and the thruster throttle table was estimated based on the

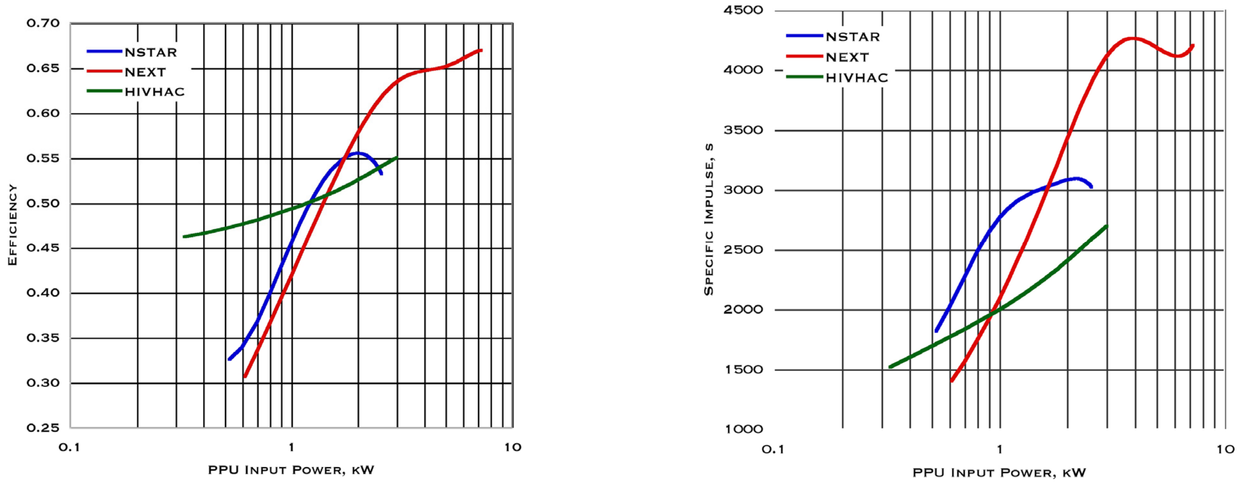

Figure 3.—The estimated performance of the HIVHAC Hall thruster.

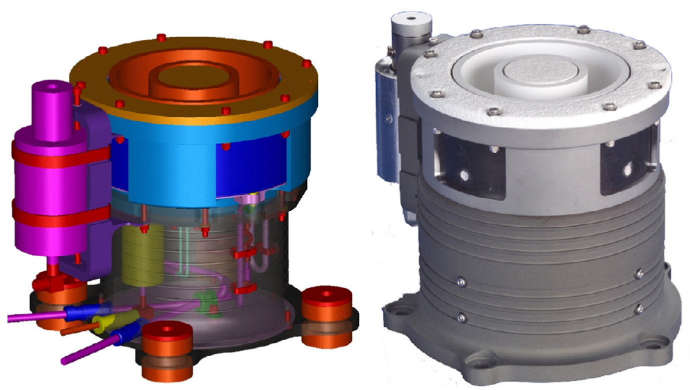
Figure 4.—NASA-77M solid model and hardware.

experimental data of existing NASA Hall thrusters. The operational power level and corresponding thruster efficiency and specific impulse at which the HIVHAC Hall thruster was designed to operate are shown in figure 3. The performance of other candidate electric propulsion devices for these applications is also presented.

Prior to the refocus activity, a NASA-170M Hall thruster was designed by NASA GRC and the Aerojet Corporation (ref. 19). This thruster incorporated features of a NASA Hall thruster that demonstrated efficient, high-voltage operation (ref. 20). Following the redirection of the HIVHAC project, the team used the same approach to design a device to operate at 0.3 to 2.8 kW. A thruster, designated the NASA-77M, was designed with an outer discharge channel diameter of 77 mm. NASA GRC designed the discharge channel geometry and magnetic circuit configuration and Aerojet performed the mechanical and thermal analysis and design. To achieve the goal of efficient operation at low power, the team developed an optimized magnetic circuit configuration, minimized the power consumed in the electromagnets and propellant required for operating the hollow cathode. The goal of minimizing the recurring cost was addressed by minimizing the number of parts and designing components with ease of manufacturing as criteria. By leveraging Aerojet's expertise in the development of flight Hall thrusters (ref. 21), a development model NASA-77M was produced, which was higher fidelity than a typical laboratory model Hall thruster. A solid model and photograph of the NASA-77M hardware are shown in figure 4.

The NASA-77M thruster was fabricated by Aerojet and delivered to NASA GRC in early 2005. A 6.35 mm NASA developed hollow cathode, that was based on the NEXT neutralizer cathode but modified for lower current operation (ref. 22), was integrated with the thruster and experimental performance testing was conducted in NASA GRC's Vacuum Facility 12. Additional details regarding the NASA-77M development and the results of this investigation were published in reference 23.

C. Out-Year Plan

Revision of the future plans for the HiVHAC project was necessary due to the redirection of the technology development to lower power. In fiscal year 2006, the HiVHAC project will address the technical challenges associated with Hall thruster lifetime and a second generation NASA-77M will be designed to demonstrate a strategy to extend Hall thruster lifetime. An improved low current hollow cathode will also be designed for the specific operational envelope of the NASA-77M. The operation of the second generation NASA-77M and low current hollow cathode will be demonstrated.

IV. Project Prometheus-Hall Thruster Research Task

A. Programmatic Background

NASA’s Project Prometheus is developing nuclear power and propulsion technologies that are enabling for NASA’s mission to explore the universe and search for life. In addition to the technology development being conducted for near term Prometheus missions, the Advanced Systems and Technology (AST) project is sponsoring broad-based research and development efforts for future exploration applications. One such activity is the investigation of high-power, high specific impulse Hall thrusters.

The objective of the AST Hall task is to reduce the technical risk of developing high-power Hall thruster propulsion for future Prometheus applications. The AST sponsored activity is focused on high-power Hall thruster research and development for applications requiring specific impulses beyond that of state-of-the-art Hall thrusters. The use of krypton propellant, which has a lower molecular weight then xenon, was investigated as a means to achieve the desired specific impulse. The initial experiments utilized an existing high-power Hall thruster, originally developed to demonstrate Hall thruster scaling to 50 kW (ref. 24), to demonstrate discharge specific impulse of 4500 seconds and discharge efficiencies up to 64 percent (ref. 25). Subsequently, a new high-power Hall thruster, designated the NASA-400M, was specifically designed to investigate high-specific impulse operation. Experimental investigations were conducted to evaluate thruster performance and to characterize the erosion operating on krypton propellant. The fiscal year 2005 effort is addressing the technical challenges associated with the interaction between a high-power Hall thruster and power processing unit (PPU) type discharge power supply.

B. FY05 Technical Accomplishments

In FY04, the performance of the NASA-400M Hall thruster was measured with the thruster operating on xenon and krypton propellants. Performance was measured at input power ranging from 4 to 65 kW. Operating on krypton propellant, discharge specific impulses up to 4940 seconds were demonstrated, which is the highest known specific impulse achieved with a compressed gas Hall thruster. A subset of these data were previously reported in reference 19 and a complete description of the performance investigation and discussion of the results were reported in reference 26.

Following the completion of the NASA-400M performance testing, the thruster was operated for an extended duration to investigate the erosion characteristics of a high-voltage, krypton Hall thruster. The test was conducted at a discharge voltage of 700 V and a discharge current of 53 A, which corresponded to 37 kilowatts. At these conditions, the discharge was stable and the discharge efficiency and specific impulse were 65 percent and 4000 seconds. The thruster was operated for 292 hours and measurements of the discharge channel erosion were made at 86, 220, and 292 hours using a laser profilometry measurement technique (ref. 27). The volumetric erosion rate was calculated and determined to be consistent with the erosion measured for other Hall thrusters over the same duration (ref. 26). The experiment was discontinued prior to the planned 1000 hours of operation due to anomalous behavior which led to a failure of the thruster. The cause of the unexpected operational characteristics are unknown, but may be attributed to sputtered material deposited on the thruster.

While the technical challenges associated with integrating Hall thrusters and power processing units have been addressed at lower power levels (ref. 28), potential integration issues at high-power are not well understood. This uncertainty exists because all high-power Hall thruster testing performed to date has utilized transformer-based, laboratory model discharge power supplies. The FY05 AST Hall thruster task investigated the interaction of a high-power Hall thruster and a power processing unit type discharge power supply. The development of a modular, high-power, DC-DC converter based discharge power supply was initiated. Two, 10 kW modules were designed, fabricated and bench-top tested at full power. One of these breadboard modules is pictured in figure 5. Integrated testing of the 20 kW discharge supply and high-power Hall thruster will be conducted to investigate thruster/power processing unit interactions, output filters requirements, start transients, regulation of discharge current and current sharing between power modules.

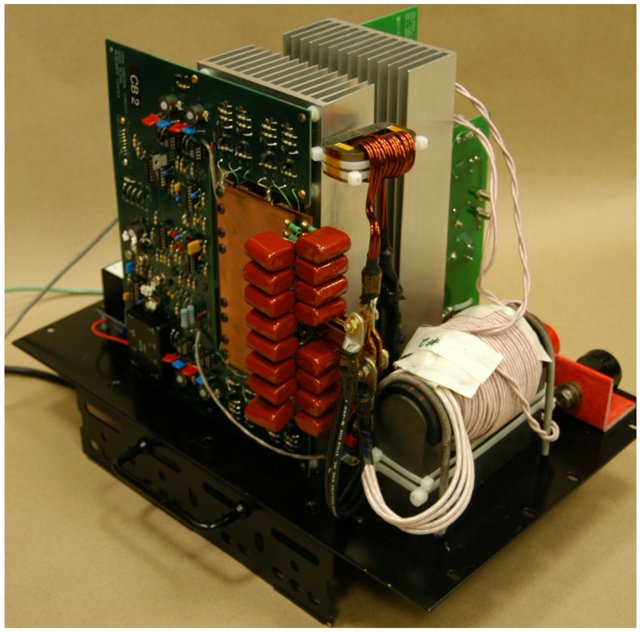

Figure 5.—The 10 kW Hall thruster DC-DC converter discharge module.

C. Out-Year Plan

The future technical content of the Prometheus Advanced Systems and Technology Hall task is not presently defined. However, continued development of high-power Hall thrusters and Hall thruster systems will enable more timely implementation of the technology for future high-power missions. Conducting integrated testing of a high-power Hall thruster and 20 kW discharge module addresses aforementioned technical challenges, which need to be considered to advance the TRL. Future activities may involve the design, build and demonstration of a breadboard PPU including all the auxiliary power supplies required to operate a Hall thruster. Future work may include PPU development at power levels in excess of 20 kW, which is facilitated by the modular approach employed in the development of the discharge supply.

V. Summary

NASA GRC is developing Hall thruster technology for NASA applications including high efficiency cargo delivery in support of the exploration initiative as well as Discovery and New Frontiers class space science missions.

These activities include the development of 100 kW class Hall thruster technology, high-current hollow cathodes and a concept to significantly extend Hall thruster lifetime under an Exploration Systems Research and Technology project. Phase II plans include detailed mechanical and thermal analysis, fabrication and demonstration of 100 kW class Hall technology. NASA GRC will also be supporting an Aerojet Corporation system development, which will utilize NASA's thruster design.

To address the needs of space science mission planners, NASA GRC is developing a 0.3 to 2.8 kW Hall thruster. A development model thruster was recently designed, fabricated, and experimentally demonstrated. The thruster features the ability to operate at low power which is critical for missions to destinations distant from the sun, and to efficiently throttle over a wide range of input power. The thruster was designed to minimize recurring cost, which is critical for cost capped NASA missions, by reducing parts and improving the easy of fabrication. Mission analysis was conducted to illustrate the mission benefit compared to a comparable ion thruster system for various applications. The out year activities will address the remaining technical challenges associated with demonstrating steady-state thermal operation and the thruster lifetime required for target missions.

A moderately high-power Hall thruster development task was conducted to reduce the technical risk of developing this type of system for future high-power NASA missions. An investigation was conducted to determine the feasibility of high-power, high-specific impulse Hall thrusters. Utilizing krypton propellant, specific impulses approaching 5000 seconds were demonstrated. Subsequently, the thruster was operated at nearly 40 kW for 292 hours to characterize the erosion operating at these conditions. A 20 kW power processing unit type discharge supply is currently being developed to address the technical challenges associated with integrating the thruster and power source.

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13. ABSTRACT *(Maximum 200 words)*

An overview of Hall thruster research and development tasks conducted by the National Aeronautics and Space Administration's John H. Glenn Research Center during fiscal year 2005 is presented. The tasks described include the investigation of scaling Hall thrusters to power levels up to 100 kW, the development of a hollow cathode capable of providing emission current up to 250 Amperes, an experimental performance investigation and erosion characterization of a high-power, high-specific impulse Hall thruster, and the design and demonstration of a 0.3 to 3.0 kW Hall thruster. For each task, a description of the program background, mission application, technical accomplishments and out year plans are provided.

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